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SHOT-PEENING INTENSITIES VS. EDDY CURRENT SIGNALS AS SEEN IN ITERATIVE TREATMENT-MEASUREMENT EXPERIMENT

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ABSTRACT. We report on progress in a swept high frequency eddy current (SHFEC) technique for characterization of surface residual stress on shot-peened superalloy surfaces. Our aim here is to demonstrate the sensitivity of our measurement for practical shot peening intensities, i.e. at 4~6A. First, we present our improved probe and instrumentation being sufficiently sensitive to resolve the surface conditions at these low Almen intensities, where our earlier measurements encountered noise problems. The previous coil was also larger (18mm in diameter) than desirable. Our new probe integrates smaller coils (12 mm in diameter, forming an AC bridge) and on-board electronics on a common printed circuit board, mutually connected at the shortest possible distance. The operational-amplifier-based electronics acts as impedance buffers, and maintains the cabling impedance at the characteristic 50Ω between the probe board and the instruments. We have thus reduced the instrumentation noises. Second, we present the result of an iterative treatment-measurement experiment, performed on a 2"-by-3" Inconel 718 block specimen, initially polished to a mirror finish. After an initial baseline SHFEC measurement, we performed shot peening, an Almen strip deflection measurement, and a SHFEC measurement as one iteration cycle, and repeated the cycles multiple times at predetermined intervals. We will show the resulting SHFEC signals (i.e. lift-off normalized vertical-component signals) plotted against the Almen intensities. We then draw several conclusions from the experimental data, including a) the SHFEC signals increase monotonically in correlation with the Almen intensity increase, and b) the SHFEC signals exhibit sufficient deviations to resolve 4~6A intensities, while c) the SHFEC signals indicate saturation of the Inconel 718 response against peening, but the saturation occurs later in the iteration than indicated by the A-series Almen strip.

Keywords: Eddy Current, Residual Stress, Shot Peening
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INTRODUCTION

Our research group at CNDE has been developing high-frequency eddy current (EC) methodology for residual stress characterization applicable to shot-peened Ni-base superalloys for the last few years [1-3]. For the previous work, we fabricated a passive pair of single-layer circular coils on a printed circuit board (PCB) [2], connected them into an AC bridge, and drove them by a network analyzer in the swept frequency mode. From

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the swept high-frequency EC (SHFEC) data thus obtained, we demonstrated determination of the surface conductivity deviation profile by means of physics-model-based inversion.

We had two main questions to address at that time: one was that, although our measurement sensitivity was positively demonstrated at higher Almen intensities of 7A through 17A, operational capabilities at industry standard peening intensities of 4~6A were yet to be demonstrated. The second question had to do with the so-called piezoresistivity relation, or the fundamental relationship between the conductivity deviation and the residual stress state, which would allow us to convert the conductivity deviation profile into the residual stress profile. Since we observed that the inverted conductivity deviation profile differs from the XRD-measured residual stress profile in the functional form, we were convinced that the naïve point-by-point application of the piezoresistivity relation does not explain the relationship between the conductivity and stress profiles correctly. Clearly, the question amounts to asking how the surface material reacts against the peening treatment and how the material state gets modified in response. We thus launched into studies of microstructural influence on the apparent piezoresistivity relation, first examining the possibility of texture effects [3]. More recently, we begin to investigate other microstructural influences (especially of the secondary γ' and γ" phases) on the electrical conductivity, and their role in the shot-peening induced conductivity variations.

Correspondingly, the objective of the study presented here is two-fold: First, we upgrade the measurement hardware for improved sensitivities, and demonstrate the effectiveness of the SHFEC method at standard peening intensities of 4~6A. Second, we examine the surface material response against shot peening, except that, here, we study the influence of shot peening on macroscopic property measurements. Ideally, it would be most desirable to perform measurements such as EC and hardness in real time while the peening is being performed. However, since the peening chamber environment is not compatible with such material property measurements, we employed the second best approach by repeated applications of treatments and measurements in iteration. This study by iteration also examines the saturation behaviors of superalloys against shot peening, as explained in the subsequent section.

INSPECTION HARDWARE UPGRADE

Previously, the EC sensitivity was insufficient for peened surfaces at low Almen intensities, limited predominantly by the cabling-effect noise. Also, it was desired to re-design the probe coil of a smaller diameter than 18 mm, but found impossible without any noise reduction. Since we routinely use the vertical component (the imaginary part) of the lift-off normalized signal deflections, the effects of the transfer function and the lift off are largely suppressed [1,2,4]. Nevertheless, even this method does not tolerate significant fluctuations of the transfer function, particularly those caused by movements of the cables that are connecting terminals of mismatched impedance.

We therefore employed the strategy to suppress the cable effects by enforcing the impedance matching at any terminals to which potentially movable coax cables are connected. Since coils have varying impedance inherently, one needs impedance buffer amplifiers between the coil elements and the lead cable terminals. Such impedance buffers had better be placed in the close proximity of the coil elements, so that the attached coax cables are driven at the characteristic 50Ω impedance, while the lines between the coil elements and the amplifiers are kept as short and rigid as possible. Our solution to meet the requirement has been developed and implemented in the probe assembly illustrated in Fig. 1. As shown, two 14-turn PCB coils of a 12 mm diameter are fabricated on a PCB as the sensing and balancing coil pair. The coil board is soldered to another PCB that holds

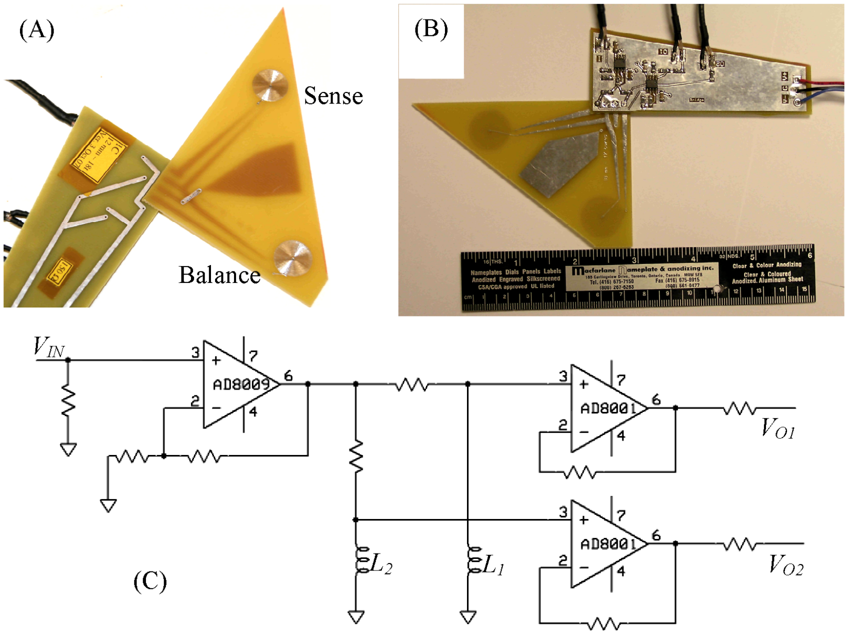

FIGURE 1. (A) 14-turn PCB coil pair, 12 mm in diameter, on a PCB used as the sensing and balancing coils. (B) Impedance buffer amplifier board consisting of the two RF operational amplifier ICs. (C) Schematics. The inductors L_1 and L_2 represent the sensing and balancing coils.

impedance buffer amplifiers, consisting of two RF operational amplifier ICs, connected to the coils via the schematics shown. The input and output impedance is set to 50 Ω to match the coax cable impedance. The input is connected to the drive source of the network analyzer, while the two output lines are connected to an external differential amplifier (LeCroy DA1855A) for detecting small sensing coil output [4]. The output of the differential amplifier returns to the receive terminal of the network analyzer.

TREATMENT-MEASUREMENT ITERATION

To perform the aforementioned treatment-measurement iterations, we used several steps: Shot peening was performed by a commercial blast cabinet custom-fitted with a 2-axis stepper-motor-controlled motion stage [5]. The peening pressure and motion speed were respectively set to the lowest and highest possible values, so that a minimum amount of peening is performed per a single pass, yet without compromising the uniformity and stability. We selected a pristine 2"-by-3" Inconel 718 block specimen with the surface polished to a mirror finish. Each sample peening was accompanied by peening of A-series Almen strips to keep track of the peening intensity progression.

In terms of measurements, we performed, after each iteration, deflection measurements of the Almen strips, as well as the SHFEC data acquisition and surface roughness measurements by profilometry. Base-line SHFEC measurements were also performed on the pristine Inconel 718 block before any treatment begins.

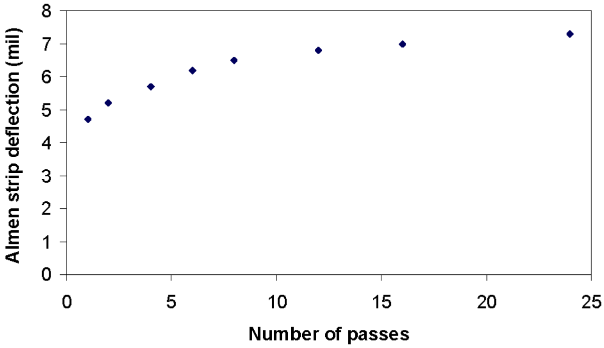

FIGURE 2. Progression of the Almen strip deflection as a function of the shot peening passes. Prototypical saturation behavior of Almen strips is reproduced in this experiment, showing steady peening performance.

RESULTS OF TREATMENT-MEASUREMENT ITERATION

Progression of Almen Deflection and Surface Roughness

The Almen strip deflection is known to progress rapidly in the early stage of the treatment, and then rather swiftly approaches saturation, the behavior being observed in this experiment as shown in Fig. 2. This Almen deflection progression is compared below with the progressions of the other material properties.

It is also known that the surface roughness, as seen by the profilometry, remains virtually unaffected by the peening treatment, or rather starts to decrease in the over-peening conditions. Our data, shown in Fig. 3, are consistent with this general observation.

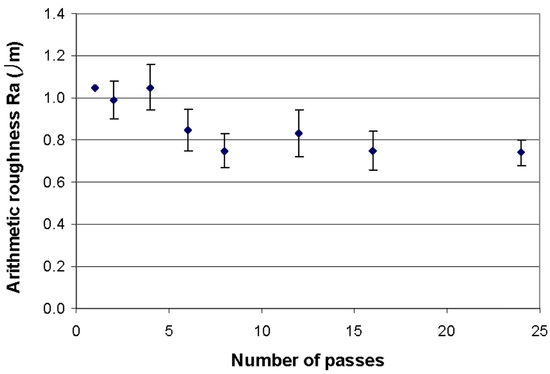

FIGURE 3. Progression of the surface roughness as a function of the shot peening passes. The roughness, as seen by the profilometry, is known to decrease in the over-peening conditions, as seen here.

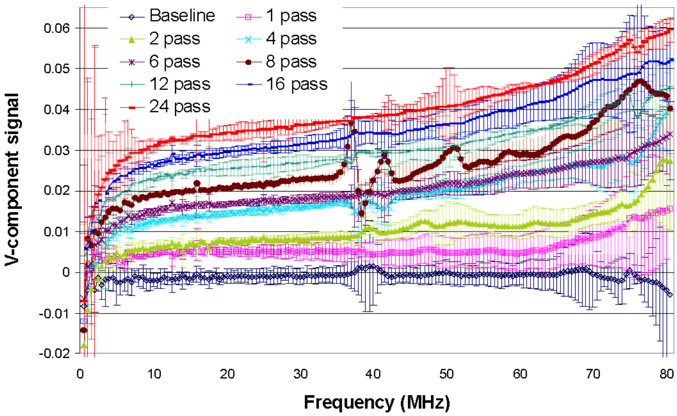

FIGURE 4. Cumulative compilation of the swept frequency EC data (the lift-off normalized vertical component signals) as functions of the frequency for the multiple peening passes, taken at the baseline condition, after one pass, after 2 passes, and so forth, until after the iteration was stopped at 24 passes.

Progression of Swept High Frequency EC Signals

The most interesting in this iteration study is the progression of the SHFEC signals as a function of the peening passes. Five repetitions of the SHFEC measurements were taken at each step of the iteration, as well as in the baseline condition, from which the average swept frequency EC data with the error bars were determined. The results are plotted collectively in Fig. 4. The data clearly show steady, monotonic increase in the EC vertical component signals as the number of passes increases. It can be seen also that the data after 4 passes and 6 passes, for example, are clearly distinguishable. According to the strip deflection data in Fig. 3, these passes correspond to the Almen intensities of 5.8A and 6.2A, respectively, providing evidence for the sufficient intensity resolution of our SHFEC measurements.

To compare the monotonic increase in SHFEC signals with that of the Almen strip deflections, we took vertical slices of Fig. 4 at the frequencies of 15, 20, 25, and 30 MHz, and re-plotted the signal progressions against the peening passes in Fig. 5, in comparison

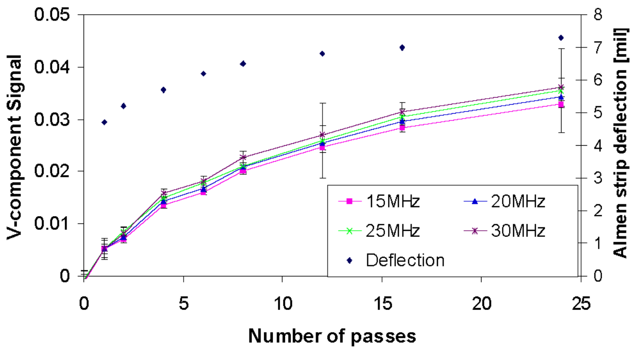

FIGURE 5. Progression of the SHFEC signals as a function of the shot peening passes. The data is obtained from those plotted in Fig. 4 by taking cross sections at the indicated frequencies. The Almen deflection data of Fig. 2 are reproduced here for comparison, with the vertical axis on the right.

with the Almen deflection progression. A significant difference can be seen in the initial increases between the strip deflections and EC signals: Namely, EC signals do not increase rapidly at the small numbers of iterations, unlike the rapid rise of the Almen strip deflections. Since residual stress is believed to correlate well with the strip deflections, the stress intensity in the Almen strip is expected to rise rapidly at small number of passes, while the EC signals do not exhibit similarly fast rise. This discrepancy provides a strong circumstantial evidence for the speculation that some effects other than stress are contributing non-trivially to the surface conductivity deviations.

The EC signals also continue to increase even after Almen strip deflections show saturation at around 8 passes. However, even the EC signals appear to indicate saturation above 16 passes, as seen by the slowdown of the rate of increase between 16 and 24 passes. This difference in reaching saturation is presumably due to the material difference, i.e. Almen strips being made of steel, while EC data are taken from the Inconel 718 sample that has much higher yield strength than steel.

Consistency Test of the EC Data via Scaling Behavior

In a companion paper, we introduced a notion of scaling behaviors of several material property deviation profiles. What is relevant here is the scaling of the vertical component EC signals $V(f)$ as a function of the frequency f, namely

$$V(f) \propto d \cdot F(fd), \tag{1}$$

where d denotes the Almen strip deflection, and where $F(x)$ is a universal function of the argument x [6]. The scaling behavior described by Eq. (1) can be tested by the universality of the scaled plots in Fig. 6, where the scaled V-component signals $V \cdot (d_0/d)$ are plotted against the scaled frequency $f \cdot (d/d_0)$, relative to the largest deflection d_0 (=7.3 after 24 passes). The universality is poor before 6 passes, and becomes better after 8 passes. This is consistent with the fact that the scaling law is assumed to hold under saturation, while Inconel 718 appears to reach saturation later after 16 passes.

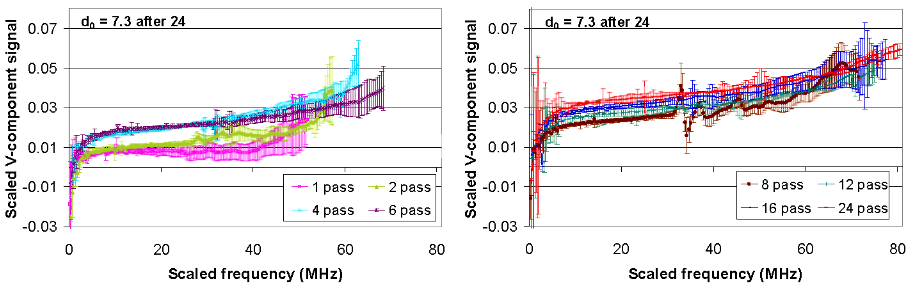

FIGURE 6. The same swept frequency EC data (the vertical component signals) as given in Fig. 4 for the multiple peening passes, except that, here, the scaled V-component data, $V \cdot (d_0/d)$, are plotted against the scaled frequency, $f \cdot (d/d_0)$, in order to test the predictions of the scaling law, which holds poorly at small numbers of passes (on the left), while holding reasonably well at higher passes (on the right).

CONCLUSIONS

This paper reports on the improvement of the EC characterization hardware in terms of the upgraded PCB coil sensors with built-in electronics. The electronics involves impedance buffer amplifiers, so that the signal coax cables in and out of the probe board are driven at the standard 50Ω impedance. It is demonstrated that the resulting SHFEC measurement system is sufficiently sensitive to discriminate surfaces peened at varying Almen intensities around 4~6A, shown as a part of the treatment-measurement iteration experiment.

In addition, the results of the treatment-measurement iteration have explicitly verified that the EC signals increase monotonically in correlation with the increase of the Almen strip deflection. The EC signals indeed approach saturation, indicating the slowing down of the specimen response against increased peening passes, with the resulting slowdown in conductivity increase. However, the saturation in the EC signals occurs later in iteration than indicated by the saturation of Almen strip deflections. This is consistent with the fact that Ni-base superalloys such as Inconel 718 have higher yield strengths than the steel material, from which Almen strips are made.

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